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### *Effects of high-sugar grasses and improved manure management on the environmental footprint of milk production at the farm level*

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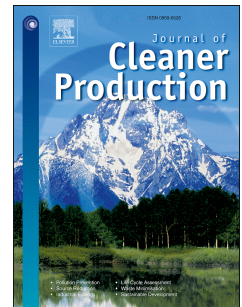
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# Accepted Manuscript

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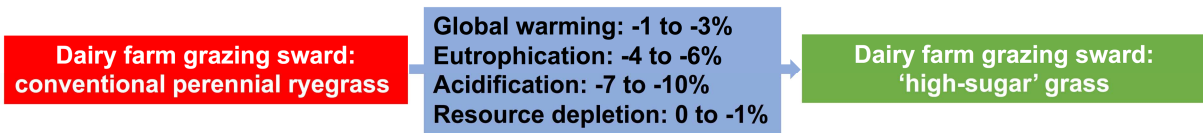
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**Effects of high-sugar grasses and improved manure management on the environmental footprint of milk production at the farm level**

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**ABSTRACT**

Pasture-based milk is increasingly preferred by consumers owing to its perceived socio-economic, animal welfare and environmental benefits. However, nitrogen excretion from pasture-based dairy farming is also a large source of nitrogen leaching and emission of the potent greenhouse gas nitrous oxide. Ryegrass bred to express elevated concentrations of water-soluble carbohydrates ('high-sugar' grass; HSG) has been shown to decrease dietary nitrogen excretion in urine of cattle, and may increase milk yields per cow, but it is unclear how this translates to environmental footprints at the farm- and product-levels. This study evaluates, for the first time, the environmental footprint of HSG dairy systems with life cycle analysis, measured as land occupation in addition to global warming, eutrophication, acidification and resource depletion potentials (energy-based and economic allocation

methods). Data from meta-analysis and simulation were combined to model a pasture-based dairy farm under a conventional perennial ryegrass-based scenario (Sc-CTR) and an HSG-based scenario (Sc-HSG). In addition, grass type interactions with six manure management permutations were considered, leading to 12 scenarios in total. It was found that eutrophication and acidification potentials per unit of energy-corrected milk could be reduced by 4–6% and 7–11% respectively when switching from Sc-CTR to Sc-HSG, and that these reductions could reach 22% and 40% respectively with more efficient manure management. It is concluded that a simple change in choice of grazing sward may deliver substantial environmental gains, especially when combined with improved farm technology. However, the high costs for improving manure management could drive expansion of HSG pastures as a more attractive short-term measure for farmers, while regulation and access to capital could drive investment in improved manure storage infrastructure and spreading equipment.

Keywords: Life Cycle Analysis; Dairy production; High-sugar grass; N excretion; Manure management; Dairy farm scenario modeling

## 1. Introduction

So-called ‘high-sugar grasses’ (HSG) are grasses that have been bred to express elevated concentrations of water soluble carbohydrates which help utilization of N released from forage digested in the rumen of ruminant livestock (Parsons et al., 2004). When fed to dairy cows and other livestock, HSG have potential to significantly reduce the proportion of ingested N that is lost in urine, thus reducing N leaching and emissions of the potent greenhouse gas  $N_2O$  (Foskolos and Moorby, 2017; Parsons et al., 2004). In addition, there is evidence that HSG increase milk and milk protein yields (Keim and Anrique, 2011). Combined with other socio-economic and environmental benefits of grazed grasses compared

with crop-based feeds (e.g. increased carbon sequestration in soil, enhanced macro-scale biodiversity of the production system or high nutritional value of grass-based milk; Nguyen et al., 2013), there is a large scope for engineering current grasslands by growing HSG to increase the sustainability of milk production.

Existing knowledge on the potential of HSG to deliver more sustainable milk production has not previously been evaluated at the whole-farm system level, from a life cycle analysis (LCA) perspective. Life cycle analysis is a methodology that can be used to estimate whole-system resource use and environmental impacts (Ledgard et al., 2003). Thus, it can be used to expand the focus that HSG-based dairy farming systems have received in terms of urinary N excretion towards other potent environmental pollutants from dairy farming, such as CH<sub>4</sub>, for which few HSG dairy studies exist (Bertilsson et al., 2017; Ellis et al., 2012; Staerfl et al., 2012).

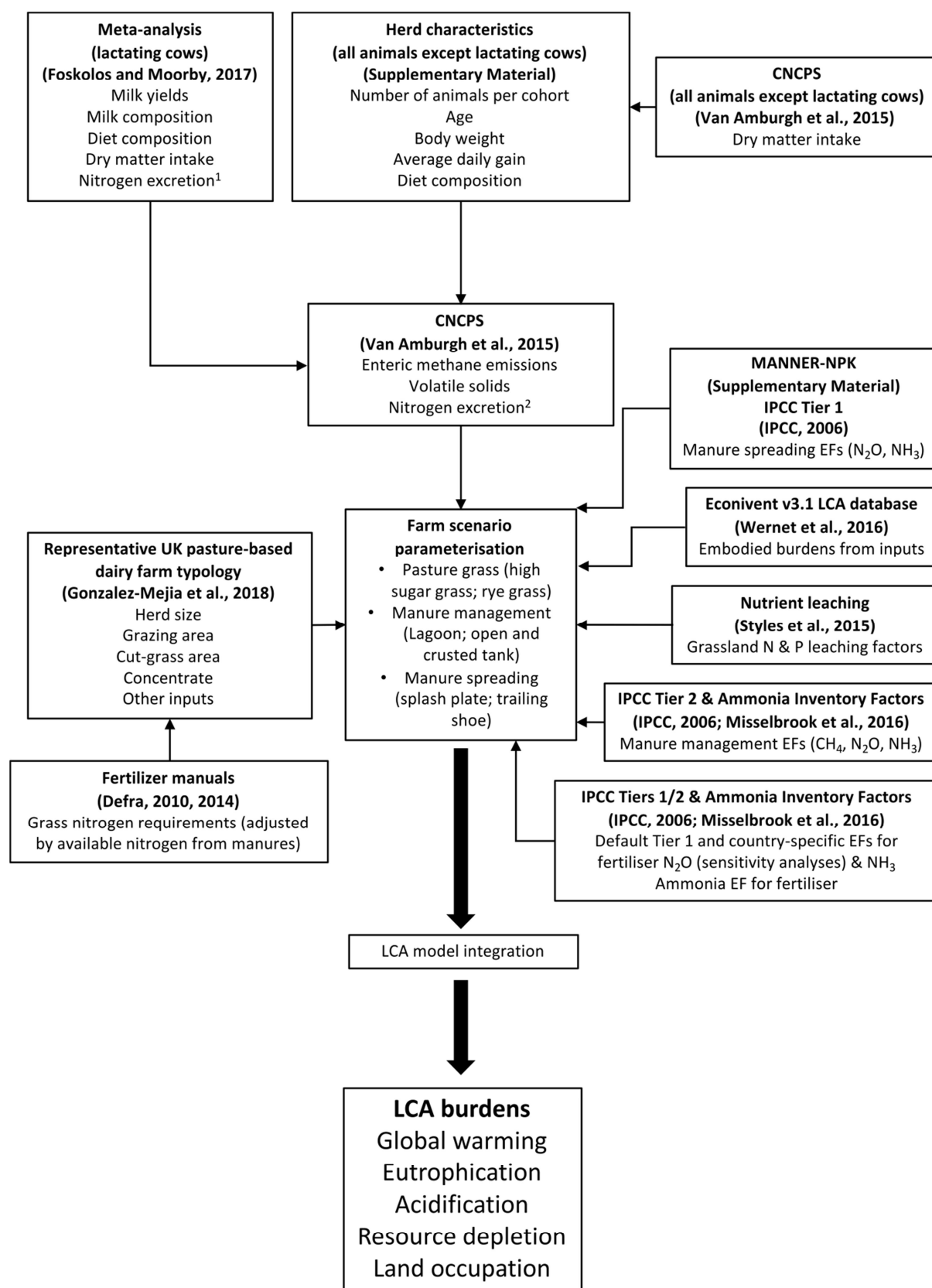
Understanding the potential of HSG from an LCA perspective is particularly important for grass-based dairy farming systems for two main reasons. First, many pasture-based dairy farms rely heavily on grass as a feed, via grazing fresh grass and the use of conserved grass forage fed indoors (March et al., 2014). Second, dairy farms have been undergoing a long-term trend of consolidation and intensification over the past few years (March et al., 2014; van Berkum and Helming, 2006), and new evidence suggests that larger, grass-based dairy farming systems are one of the emerging dominant typologies in the UK (Gonzalez-Mejia et al., 2018). Given this trend and the continuing debate about whether or not intensifying dairy farming can mitigate climate change emissions while maintaining or increasing milk production (Soteriades et al., 2016; Styles et al., 2018), it is important to evaluate the role of HSG in helping intensify dairy production more sustainably.

The objective of this study is to investigate the environmental footprint of HSG as a forage source in pasture-based dairy farming. For this purpose, two main scenarios were

developed based on a 'typical' UK dairy farm (March et al., 2014) that differed in the forage source: 'conventional ryegrass' *versus* 'high-sugar grass'. As manure management also has a strong influence on emissions arising from dairy farms (Chadwick et al., 2011; Misselbrook et al., 2016), and consequently on livestock environmental footprint calculations (Styles et al., 2015) the interaction with forage source was also tested. Given the potential influence of HSGs on manure emissions, especially via changes in N excretion product outputs and subsequent use of these as a nutrient resource, scenario permutations were generated where the type of manure storage facility and the manure spreading methods were varied in each system, to capture the interaction effect that these technological and managerial choices can have on dairy farm environmental performance (Styles et al., 2015). The two main scenarios were modelled with prominent farm- and animal-scale simulation (Gibbons et al., 2006; Van Amburgh et al., 2015) to accurately represent and better understand biological and managerial responses to the different forage and manure storage types. To the best of the authors' knowledge, no earlier study has evaluated the environmental performance of HSG with LCA.

## **2. Materials and methods**

In this study, the use of HSG in dairy farming was evaluated in terms of five major LCA environmental impacts: global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), fossil resource depletion potential (RDP) and land occupation (LO) (Castanheira et al., 2010; Guerçi et al., 2013; Styles et al., 2015). This section describes the modelled farms, LCA methods and data, and sensitivity and economic analyses that were carried out. The process is also illustrated in Fig. 1.



**Fig. 1.** Summary of methods illustrating sources of data and models used. <sup>1</sup> Grazing period. <sup>2</sup> Indoor period.



## 2.1. Dairy farm characteristics and scenarios

The dairy farm scenarios are briefly discussed here. A detailed description is available in the Supplementary Material (Section S1). Representative farm typologies (Fig. 1) were used to ensure that results relate to typical UK (and wider temperate) grazing-based dairy systems, as with previous LCA and farm modelling studies based on a 'typical' farm of a region (Basset-Mens et al., 2009; Gibbons et al., 2006; Styles et al., 2018). Along these lines, farm structure and inputs (excluding feed) were defined according to the major extensive, pasture-based dairy farm typology identified from statistical analysis of 14 years of UK dairy farm statistics (Gonzalez-Mejia et al., 2018; Fig. 1).

Animal husbandry comprised a six-month housed period and a six-month grazing period (March et al., 2014). Two different scenarios were developed for this farm based on the forage source, using information from a recent meta-analysis on HSG systems (Foskolos and Moorby, 2017) and outputs from the Cornell Net Carbohydrate and Protein System (CNCPS; Van Amburgh et al., 2015) feed model, elaborated below (Fig. 1). The first scenario consisted of conventional ryegrass (Sc-CTR) and the second of HSG (Sc-HSG), the latter being increasingly used in UK livestock holdings over the past few years (Defra, 2017). The farm typology comprised of 132 milking cows and 118 heifers on 65 ha ( $10^4$  m<sup>2</sup>) of grazed grass and 40 ha of cut grass, importing 246 Mg y<sup>-1</sup> concentrate feed. Average annual milk yields were based on the meta-analysis and were 6437 L ( $10^{-3}$  m<sup>3</sup>) per cow and 6874 L per cow for the Sc-CTR and Sc-HSG scenarios, respectively. These yields closely matched the 6835 L per cow average annual milk yield identified in the extensive farm typology derived from national farm statistics (Gonzalez-Mejia et al., 2018). As the modelled Sc-CTR and Sc-HSG diets resulted in different milk compositions the yields were converted to energy

corrected milk yields (ECM; Tyrrell and Reid, 1965) of 7136 kg and 7282 kg per cow respectively. This allowed the LCA impacts to be expressed over a standardized functional unit, as per other LCA studies of dairy production (Basset-Mens et al., 2009; Bava et al., 2014; Guerri et al., 2013).

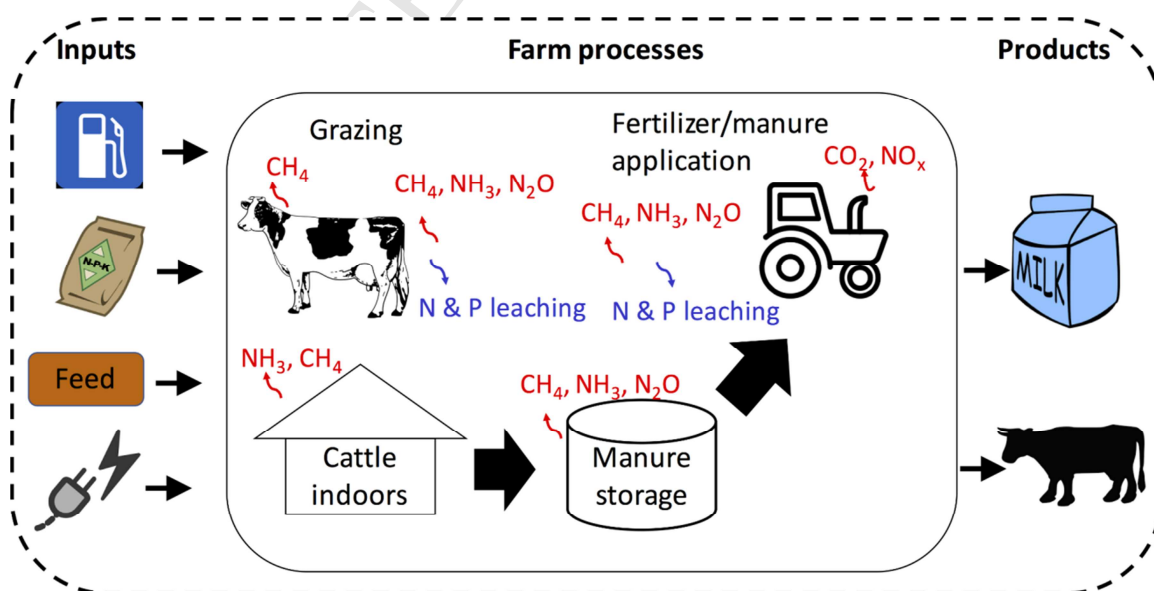
The farm was further parametrized in terms of diet composition based on the meta-analysis (Foskolos and Moorby, 2017; see also Section S1 and Fig. 1). Diet for milking cows was defined across three distinct phases (on pasture, indoors and dry period) and diet for the replacement herd was defined across four distinct phases (weaning, weaning to six months old, six months old to first service and first service to first calving). Diet input data were used to parameterize the CNCPS model that then calculated enteric  $\text{CH}_4$  emissions, volatile solids and N excretion for each animal cohort for the indoor period (CNCPS includes equations for these variables; Fig. 1). These variables were estimated with CNCPS because to obtain these data metabolic chambers are needed and no study to date has investigated the effect of HSG on lactating cows in chambers. These variables were also estimated with CNCPS for the period on pasture, except for N excretion, where data from the meta-analysis were used. Outputs were estimated per animal and day, and then aggregated to the farm level over one year of operation. Herd data were then integrated with data on housing, field and manure management operations within a farm LCA model to calculate the environmental impact of annual milk production in the scenarios (Fig. 1).

Twelve scenario permutations were derived from the two main scenarios (Sc-CTR and Sc-HSG) to represent interaction of pasture type with the range of manure management practices common across dairy farms (Defra, 2017; Gibbons et al., 2006; Styles et al., 2015). These permutations were as follows (worst- to best- practice): (i) for manure storage: lagoon storage; slurry tank without crust cover; and slurry tank with crust cover; and (ii) for manure spreading: splash plate; and trailing shoe (Fig. 1). Thus, the worst-case scenario was for

lagoon storage and splash plate, while the best-case scenario was for tank storage with crust cover and trailing shoe.

## 2.2. LCA goal and scope definition

The goal of the LCA was to compare the environmental footprint of milk produced from HSG to that of milk produced from conventional ryegrass on a pasture-based dairy farm. An attributional LCA was performed in accordance with ISO principles (ISO, 2006), accounting for upstream impacts associated with the production and transport of inputs and all major animal, manure management and field emissions on the dairy farms (Styles et al., 2015; Fig. 2). The functional unit was one kg ECM exported from the farm gate. Post-farm-gate processes were not considered, as they are not expected to differ between the two scenarios. Farm system burdens were allocated to milk based on the respective gross energy outputs of milk and body mass from culled milking cows, surplus heifers and male dairy calves (exported from the dairy farm at birth).



**Fig. 1.** Main inputs, processes and products accounted for within the system boundaries to calculate impact per kg of energy-corrected milk.

171

## 172 2.3. Life cycle inventory data

173 Data were taken from different sources including the literature, model calculations, and LCA  
174 databases. The life cycle inventory process followed two earlier LCA studies of UK dairy  
175 farms (Styles et al., 2018, 2015). For assumed emissions from inputs, animals, housing,  
176 manure management and application, and fertilizer application see Table 1. The land  
177 footprint of dairy concentrate feed was taken from the Feedprint database (Vellinga et al.,  
178 2013).

179 **Table 1.** Inputs and emissions for the Sc-CTR<sup>a</sup> and Sc-HSG<sup>b</sup> scenarios, assuming open tank slurry storage and splash-plate slurry spreading.

Stage	Process	Sc-CTR <sup>a</sup>	Sc-HSG <sup>b</sup>	Units	Methods	Comments
Inputs (quantities, and embodied burdens)	Concentrate feed	0.25		kg kg <sup>-1</sup> ECM <sup>c</sup>	CNCPS <sup>1</sup> Meta-analysis <sup>2</sup>	See Section S1.
	Diesel (field operations)	70		L ha <sup>-1</sup>	Farm-adapt <sup>3</sup>	Farm-adapt is a farm-level optimization model.
	Fertilizer-N	205	211	kg ha <sup>-1</sup>	Nutrient balance <sup>4</sup>	Fertilizer recommendations for pastures <sup>4</sup> , minus available nutrients in manure applications. Assumptions: milk yield = 6000–8000 L per cow y <sup>-1</sup> , concentrate use = 1.8 Mg per cow y <sup>-1</sup> , stocking rate = 2 livestock units ha <sup>-1</sup> .
	Fertilizer-P <sub>2</sub> O <sub>5</sub>	2.4	3.6	kg ha <sup>-1</sup>	Nutrient balance <sup>4</sup>	
	Fertilizer-K <sub>2</sub> O	52	54	kg ha <sup>-1</sup>	Nutrient balance <sup>4</sup>	
	Lime	250		kg ha <sup>-1</sup>	Agri-statistics <sup>5</sup>	
	Electricity use	350		kWh per cow y <sup>-1</sup>	Warwick HRI <sup>10</sup>	Burdens taken from Ecoinvent v.3.1 <sup>12</sup> .
Animal emissions	Enteric CH <sub>4</sub>	0.0249	0.0243	kg kg <sup>-1</sup> ECM	CNCPS <sup>1</sup> Meta-analysis <sup>2</sup>	See Section S1.
	N excretion	0.0206	0.0182	kg kg <sup>-1</sup> ECM	CNCPS <sup>1</sup> Meta-analysis <sup>2</sup>	
	Grazing NH <sub>3</sub> -N	0.06		kg kg <sup>-1</sup> TAN <sup>e</sup>	NH <sub>3</sub> inventory <sup>6</sup>	
	Grazing N <sub>2</sub> O-N	0.02/0.0044		kg kg <sup>-1</sup> TN <sup>f</sup>	IPCC Tier 2 <sup>7</sup>	It was assumed that all grass areas were re-seeded every five years, incurring N <sub>2</sub> O emissions from N mineralization calculated using an IPCC Tier 1 approach <sup>7</sup> . Indirect N <sub>2</sub> O -N emissions arising from all volatilized and leached N was also calculated using an IPCC Tier 1 approach <sup>7</sup> .
	Grazing N leaching	0.1		kg kg <sup>-1</sup> TN	LCAD tool <sup>8</sup>	
	Grazing P leaching	0.03		kg kg <sup>-1</sup> P	LCAD tool <sup>8</sup>	
Housing emissions	Milking cow NH <sub>3</sub> -N	0.041		kg per head y <sup>-1</sup>	TFRN <sup>9</sup>	Emission factors for slatted floor housing.
	Heifer NH <sub>3</sub> -N	0.012		kg per head y <sup>-1</sup>	TFRN <sup>9</sup>	
Manure storage emissions	NH <sub>3</sub> -N	0.005 – 0.55		kg kg <sup>-1</sup> TAN	NH <sub>3</sub> inventory <sup>6</sup>	
	N <sub>2</sub> O-N	0.00 – 0.005		kg kg <sup>-1</sup> TN	IPCC Tier 2 <sup>7</sup>	IPCC Tier 2 methods <sup>7</sup> , depending on manure storage type, driven by volatile solids and N excretion data from meta-analytical <sup>2</sup> and CNCPS <sup>1</sup> outputs.
	CH <sub>4</sub>	0.45 – 0.90		kg Mg <sup>-1</sup> slurry	IPCC Tier 2 <sup>7</sup>	
Manure emissions	application NH <sub>3</sub> -N	0.14 – 0.27 <sup>g</sup>		kg kg <sup>-1</sup> TN	MANNER-NPK <sup>11</sup>	Emissions and fertilizer replacement from slurry application determined by MANNER-NPK <sup>11</sup> , parametrized according to method of slurry application (splash plate or trailing shoe), period of application (spring, summer) and manure nutrient composition related to storage type <sup>8</sup> .
	N <sub>2</sub> O	0.01		kg kg <sup>-1</sup> TN	IPCC Tier 1 <sup>7</sup>	
	N leaching	0.00 – 0.179 <sup>g</sup>		kg kg <sup>-1</sup> TN	MANNER-NPK <sup>11</sup>	
	P leaching	0.03		kg kg <sup>-1</sup> P	LCAD tool <sup>8</sup>	
Fertilizer	application NH <sub>3</sub> -N	0.018		kg kg <sup>-1</sup> TN	NH <sub>3</sub> inventory <sup>6</sup>	Fertilizer application was varied according to nutrient availability

emissions	N <sub>2</sub> O-N	0.01/0.0129	kg kg <sup>-1</sup> TN	IPCC Tier 1/2 <sup>7</sup>	from manures defined by MANNER-NPK <sup>11</sup> to meet nutrient requirements <sup>4</sup> .
	N leaching	0.10	kg kg <sup>-1</sup> TN	LCAD tool <sup>8</sup>	
	P leaching	0.03	kg kg <sup>-1</sup> P	LCAD tool <sup>8</sup>	

180 <sup>a</sup>Scenario with perennial ryegrass (CTR- control). <sup>b</sup>Scenario with high-sugar grass (HSG). <sup>c</sup>Energy-corrected milk. <sup>d</sup>All expressed as weighted mean across entire grass area. <sup>e</sup>Total ammonium  
181 N. <sup>f</sup>Total N. <sup>g</sup>Depending on season. References: <sup>1</sup> Van Amburgh et al. (2015); <sup>2</sup> Foskolos and Moorby (2017). <sup>3</sup> Gibbons et al. (2006). <sup>4</sup> Defra (2010). <sup>5</sup> Defra (2014). <sup>6</sup> Misselbrook et al.  
182 (2016). <sup>7</sup> IPCC (2006). <sup>8</sup> Styles et al. (2015). <sup>9</sup> Bittman et al. (2014). <sup>10</sup> Warwick HRI (2007). <sup>11</sup> Nicholson et al. (2013). <sup>12</sup> Wernet et al. (2016).

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## 2.4. Impact assessment and interpretation

The environmental footprint of milk production was quantified in terms of global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), fossil resource depletion potential (RDP) and land occupation (LO) (Fig. 1). These five indicators represent major environmental impacts from livestock farming on land, air and waters, largely due to CH<sub>4</sub>, NH<sub>3</sub> and N<sub>2</sub>O emissions, the use of non-renewable resources and land (Steinfeld et al., 2006). In this LCA study, GWP, EP, AP, RDP and LO were expressed in the following units, based on the CML methodology (CML, 2017; Guinée et al., 2002): kg CO<sub>2</sub> equivalents (eq.), g (10<sup>-3</sup> kg) PO<sub>4</sub> eq., g SO<sub>2</sub> eq., MJ eq. and m<sup>2</sup> land, respectively, at the whole farm level and per kg ECM following energy-based allocation across milk, exported calves and culled milking cow body mass.

To compare the relative magnitudes of environmental burden changes across the five impact categories considered in this study, burdens per kg ECM were normalized against European per capita burdens. These were derived by dividing data on European environmental loadings (CML, 2017) and Europe's land area by the European Union population of 510 million people (Eurostat, 2018). The CML divisors were 10220 kg CO<sub>2</sub> eq., 0.0363 g PO<sub>4</sub> eq., 0.033 g SO<sub>2</sub> eq., 68866 MJ eq. and 8310 m<sup>2</sup> land for GWP, EP, AP, RDP and LO respectively.

## 2.5. Sensitivity analyses

Sensitivity analyses were performed on key emission factors, the housing period and allocation method.

### 2.5.1. Key emission factors

The effect of uncertainty in IPCC coefficients and emissions factors was assessed. The N<sub>2</sub>O-N emission factor applied to N excreted during grazing has recently been reduced by a factor of approximately 4.5 (from 0.02 to 0.004432 kg kg<sup>-1</sup> total N) in national greenhouse gas accounting (Brown et al., 2017), whilst the N<sub>2</sub>O-N factor applied to ammonium-nitrate fertilizer spread on grassland has increased slightly (from 0.01 to 0.01293 kg kg<sup>-1</sup> total N). These estimates were accounted for in the GWP calculations of this study.

#### 2.5.2. Housing period

Although this study models a 'typical' six-month housed period and a six-month grazing UK dairy farm, March et al. (2014) found that many dairy farms have increased the housing period over the past few years. Therefore sensitivity analysis was performed on the 12 scenario permutations by varying the number of days milking cows spent indoors from 120 to 150, 180 and 210 to test the robustness of the baseline results.

#### 2.5.3. Allocation method

The energy allocation method was used in the baseline analysis to apportion LCA burdens to milk production. A sensitivity analysis was conducted with the economic allocation method to test the robustness of the baseline results. Economic allocation was done by accounting for the production of milk and meat (cull cows, surplus calves and heifers sold as in-calf heifers; section S1). Price data per L milk produced and head calf and per heifer were taken from Redman (2017), while prices kg cull per cow were obtained from AHDB Beef & Lamb (2018). Manure was not considered in the economic allocation because all the manure is used on the farm.

#### 2.6. Economic analysis



In addition to the LCA analysis, sustainability assessments should encompass economic and social dimensions (Chen and Holden, 2018). In practice, farmers may not adopt more environmentally efficient practices unless they are financially viable. Therefore, a simple economic analysis was done on the profit gains/cost reductions that could be achieved when shifting from Sc-CTR to Sc-HSG. The focus was on milk production income, and manure storage and spreading costs, using price data from commercial UK farms (FAS, 2013; NAAC, 2017; Redman, 2017).

## 2.7. Software

All LCA calculations and results visualisations were performed in the R programming language (R Core Team, 2017).

## 3. Results and discussion

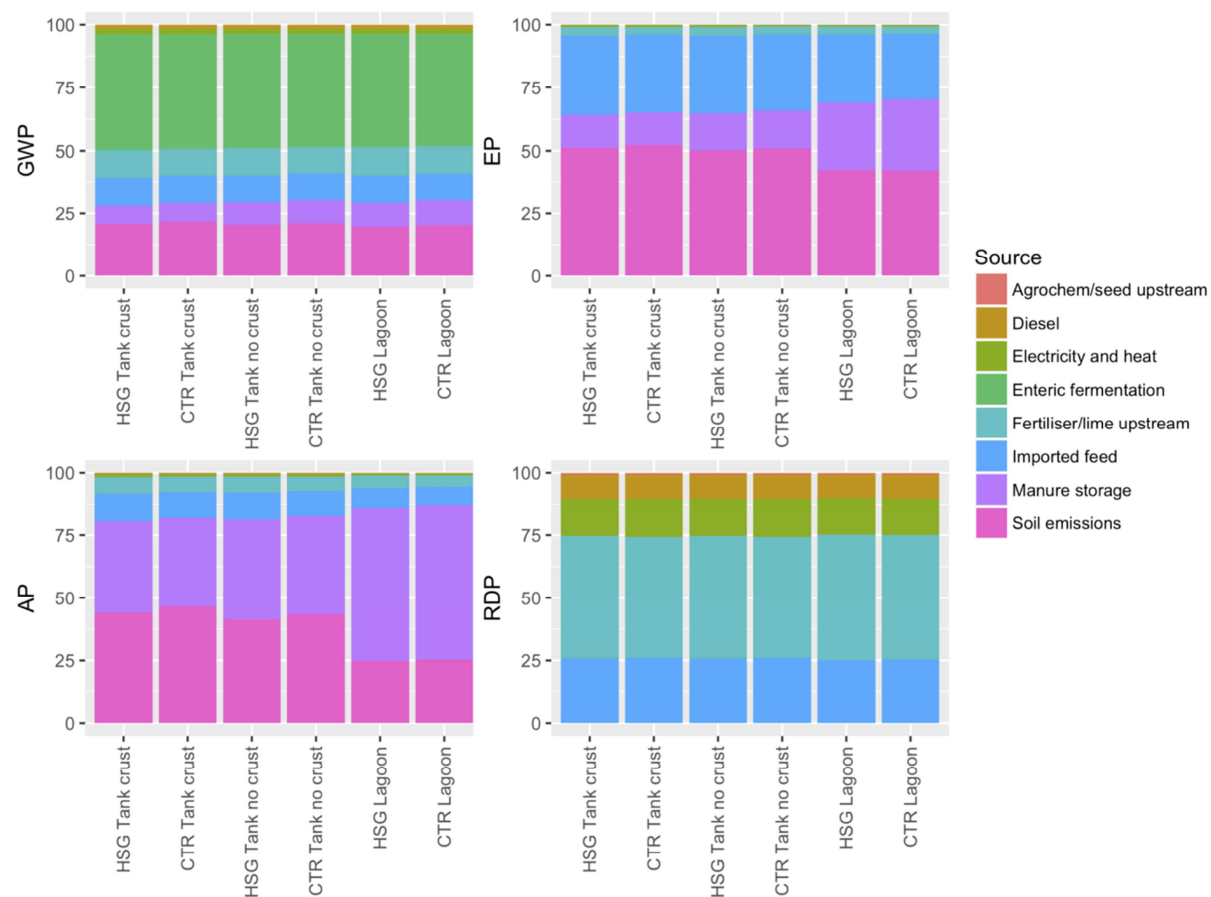
This study evaluated the potential of HSG to improve dairy farm environmental performance from an LCA perspective. While numerous earlier studies on HSG placed much focus on N excretion and sometimes on CH<sub>4</sub> emissions (Ellis et al., 2012; Keim and Anrique, 2011; Staerfl et al., 2012), this study is the first to evaluate net effects from a whole-farm system and product footprint perspective, and across a range of potent environmental impacts incurred by dairy farming, i.e. GWP, EP, AP and RDP and LO.

Twelve dairy farm scenario permutations were considered, representing six different manure management practices combined with the two main grass type scenarios (Sc-CTR and Sc-HSG). This kind of scenario permutation generation is common in the LCA literature, and enabled results for prevailing farming practices to be compared with best- and worst-case iterations (Basset-Mens et al., 2009; Styles et al., 2018, 2015), showing a considerable range in the magnitude of effect (Table 2; Fig. 3–4).

### 3.1. The effect of feed conversion efficiency on environmental footprints

The meta-analysis (Foskolos and Moorby, 2017) data indicated that HSG grasses supported 6.8% higher milk yields than conventional ryegrasses, with a 3.5% higher dry matter intake. The meta-analysis data and CNCPS simulations indicated a 12% reduction in N excretion per kg ECM at the herd-level. These translated into notable environmental savings under the default assumption of open tank manure storage and splash-plate field application of manure (Table 2), in part reflecting the larger volume of milk over which farm impacts are divided. Replacing conventional perennial ryegrass with HSG and keeping the manure storage and spreading types the same led to reductions in environmental impacts of up to 0.04 kg CO<sub>2</sub> eq. for GWP (for lagoon and for tank with crust and either trailing shoe or splash plate), 0.36 g PO<sub>4</sub> eq. for EP (for lagoon and splash plate), 1.22 g SO<sub>2</sub> eq. for AP (for lagoon and splash plate) and 0.02 MJ for RDP (for lagoon and splash plate) per kg ECM. The higher milk yields achieved by Sc-HSG also resulted in slightly lower LO per kg ECM, relative to Sc-CTR, with about 67% of each scenario's total LO per kg ECM occurring on-farm (Table 2).

The GWP saving reflects improved conversion of feed gross energy into milk, given that enteric CH<sub>4</sub> represented 44–46% of the total greenhouse gas emissions in each scenario (Fig. 3 and S1), and is proportional to gross energy intake, whilst manure management contributed a further 7–10% to greenhouse gas emissions from milk production (Fig. 3 and S1), largely related to volatile solids excretion. The larger reduction in AP reflects mitigation of NH<sub>3</sub> emissions from manure storage and spreading owing to reduced N excretion.



**Fig. 3.** Life Cycle Analysis impacts per source for trailing shoe. CTR: scenario with perennial ryegrass. HSG: scenario with high-sugar grass. GWP: global warming potential. EP: eutrophication potential. AP: acidification potential. RDP: resource depletion potential.

**Table 2.** Life Cycle Analysis impacts per kg energy-corrected milk for each grass type, manure storage facility (lagoon, tank without crust cover, tank with crust cover) and manure spreading method (trailing shoe; or splash plate in parentheses).

	<b>GWP<sup>c</sup></b>		<b>EP<sup>e</sup></b>		<b>AP<sup>f</sup></b>		<b>RDP<sup>g</sup></b>		<b>LO<sup>h</sup></b>	
	<b>(kg CO<sub>2</sub> eq.<sup>d</sup>)</b>		<b>(g PO<sub>4</sub> eq.)</b>		<b>(g SO<sub>2</sub> eq.)</b>		<b>(MJ)</b>		<b>(m<sup>2</sup>)</b>	
	Sc-CTR <sup>a</sup>	Sc-HSG <sup>b</sup>	Sc-CTR <sup>a</sup>	Sc-HSG <sup>b</sup>	Sc-CTR <sup>a</sup>	Sc-HSG <sup>b</sup>	Sc-CTR <sup>a</sup>	Sc-HSG <sup>b</sup>	Sc-CTR <sup>a</sup>	Sc-HSG <sup>b</sup>
<b>Lagoon</b>	1.18	1.14	5.82	5.50	12.09	10.98	2.56	2.54	Total:	Total:
	(1.19)	(1.15)	(6.09)	(5.73)	(12.86)	(11.63)	(2.60)	(2.57)	1.36	1.34
<b>Tank</b>	1.17	1.14	5.02	4.81	8.66	8.04	2.49	2.49	On-farm:	On-farm:
<b>(no crust)</b>	(1.18)	(1.15)	(5.40)	(5.13)	(9.72)	(8.94)	(2.54)	(2.53)	0.91	0.90
<b>Tank (crust)</b>	1.15	1.12	4.92	4.73	8.25	7.69	2.48	2.48	Off-farm:	Off-farm:
	(1.16)	(1.13)	(5.31)	(5.06)	(9.35)	(8.62)	(2.54)	(2.52)	0.45	0.44

<sup>a</sup> Scenario with perennial ryegrass (CTR- control). <sup>b</sup> Scenario with high-sugar grass (HSG). <sup>c</sup> Global warming potential. <sup>d</sup> Equivalents. <sup>e</sup> Eutrophication potential. <sup>f</sup> Acidification potential. <sup>g</sup>

<sup>h</sup> Land occupation.

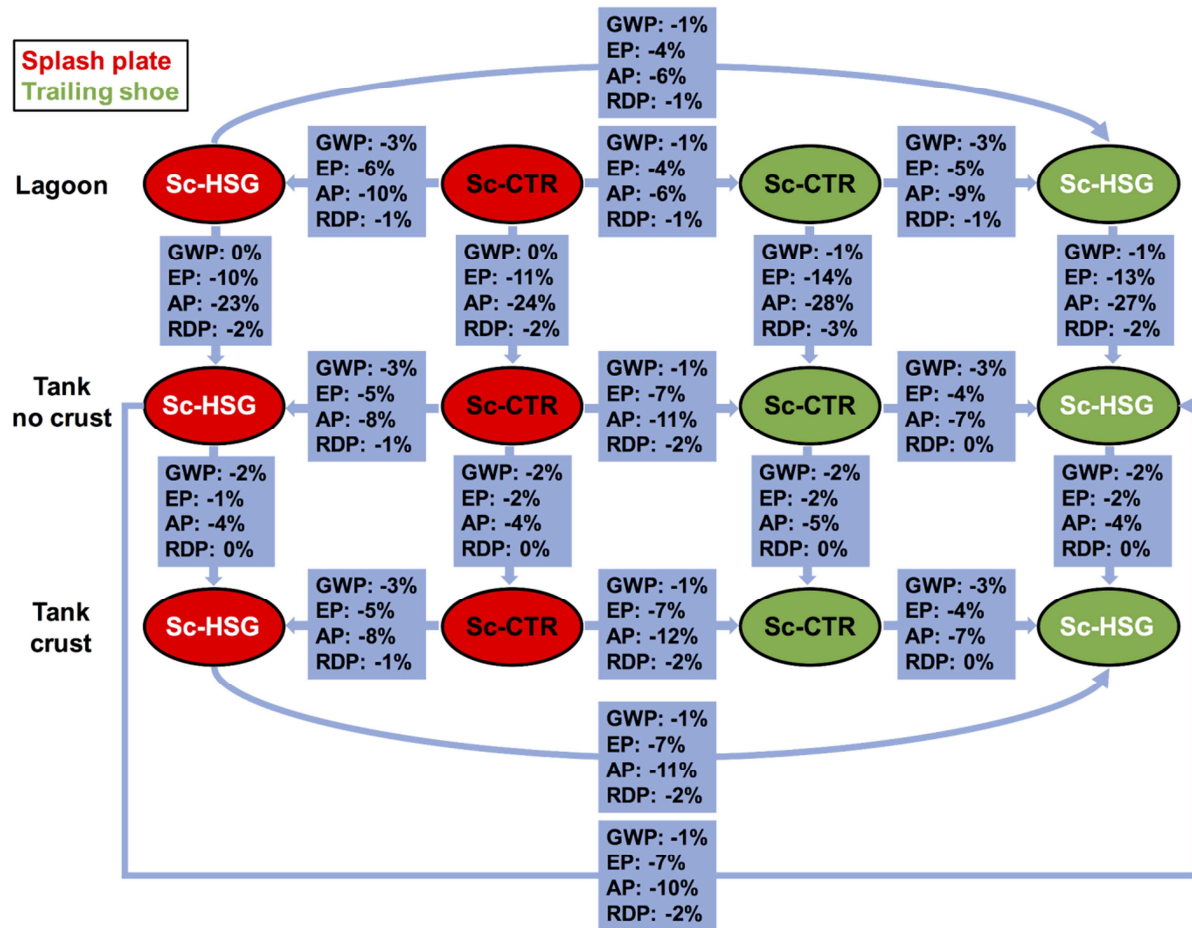
### 3.2. Interaction with manure management practices

A summary of percentage reductions in environmental impacts when shifting from perennial ryegrass to HSG and/or when improving manure storage and spreading systems is shown in Fig. 4. Under the mid-case manure management option of open tank storage and splash-plate application, switching from conventional ryegrass to HSGs reduced GWP, AP, EP and RDP impacts per kg ECM by 3, 5, 8 and 1% respectively (Fig. 4).

In addition to grass type, manure storage type and manure spreading method led to very different milk environmental footprints, expressed as impacts per kg ECM (Table 2). Environmental impacts were always reduced when conventional ryegrass was replaced by HSG and when manure storage facility type and manure spreading method were moved up the management hierarchy (e.g. from lagoon to tank with or without crust cover and from splash plate to trailing shoe; Table 2; Fig. 4). In relative terms, switching from Sc-CTR to Sc-HSG while keeping the same manure storage and spreading types reduced GWP by 3%, EP by 4–6%, AP by 7–10% and RDP by 0–1%, depending on manure storage and spreading type (Fig. 4). Scenario Sc-HSG achieved greater environmental savings under the worst manure management options, in particular for EP and AP, because of the strong influence of N excretion (manure N content) on manure and soil emissions, especially of  $\text{NH}_3$ . The largest contributors to the reductions in GWP, EP and AP were decreases in soil and manure storage emissions (4–12%; Tables S6 and S7) that occurred from the shift from perennial ryegrass to HSG. Grazing, manure storage and soil management are responsible for a large share of eutrophication and acidification impacts from dairy farming (Chobtang et al., 2016; Guerci et al., 2013) (Fig. 3 and S1). In the UK alone, grazing, manure storage and manure application to soils emit, respectively, some 28.9, 25.5 and 60.6 Gg year<sup>-1</sup> of  $\text{NH}_3$  (Misselbrook et al., 2016) and a large share of the potent greenhouse gas  $\text{N}_2\text{O}$  (IPCC, 2006). This study indicates

that a simple switch from conventional ryegrass swards to HSG swards could significantly reduce these environmental hotspots of dairy farming.

However, the current study also indicates that the mitigation potential of HSGs is limited when compared with the considerable environmental gains achievable through improved manure storage and spreading technologies. The environmental footprint of milk produced on dairy farms with conventional ryegrass pasture, lagoon storage of slurry and splash-plate application of manures could be reduced by 0.07 kg CO<sub>2</sub> eq. (or 6%), 1.36 g PO<sub>4</sub> eq. (22%), 5.17 g SO<sub>2</sub> eq. (40%) and 0.12 MJ (5%) per kg ECM respectively, if slurry storage changed to a crusted tank and application changed to trailing shoe (derived from Table 2). Figure 2 shows that: (i) switching from lagoon to tank within Sc-CTR or Sc-HSG led to small reductions in GWP (0–1%) and large reductions in EP ( $\geq 11\%$ ) and AP ( $\geq 24\%$ ); and (ii) switching manure spreading type from splash plate to trailing shoe, while keeping grass type and manure storage type unchanged, resulted in reductions of 4–7% in EP and 6–12% in AP. Reductions in RDP were generally smaller (0–3%), although, in absolute terms, this could save some 10<sup>6</sup> MJ of energy, equivalent to over 27,000 L of diesel (e.g. for Sc-CTR with trailing shoe when switching from lagoon to tank with no crust cover).



**Fig. 4.** Summary of the percent reductions in environmental impacts per kg energy-corrected milk when shifting from perennial ryegrass (CTR) to high-sugar grass (HSG) and/or when improving manure storage facility (from lagoon to tank without crust cover to tank with crust cover) and manure spreading method (from trailing shoe to splash plate). Sc-CTR: scenario with perennial ryegrass (CTR- control). Sc-HSG: scenario with HSG. GWP: global warming potential. EP: Eutrophication potential. AP: acidification potential. RDP: resource depletion potential.

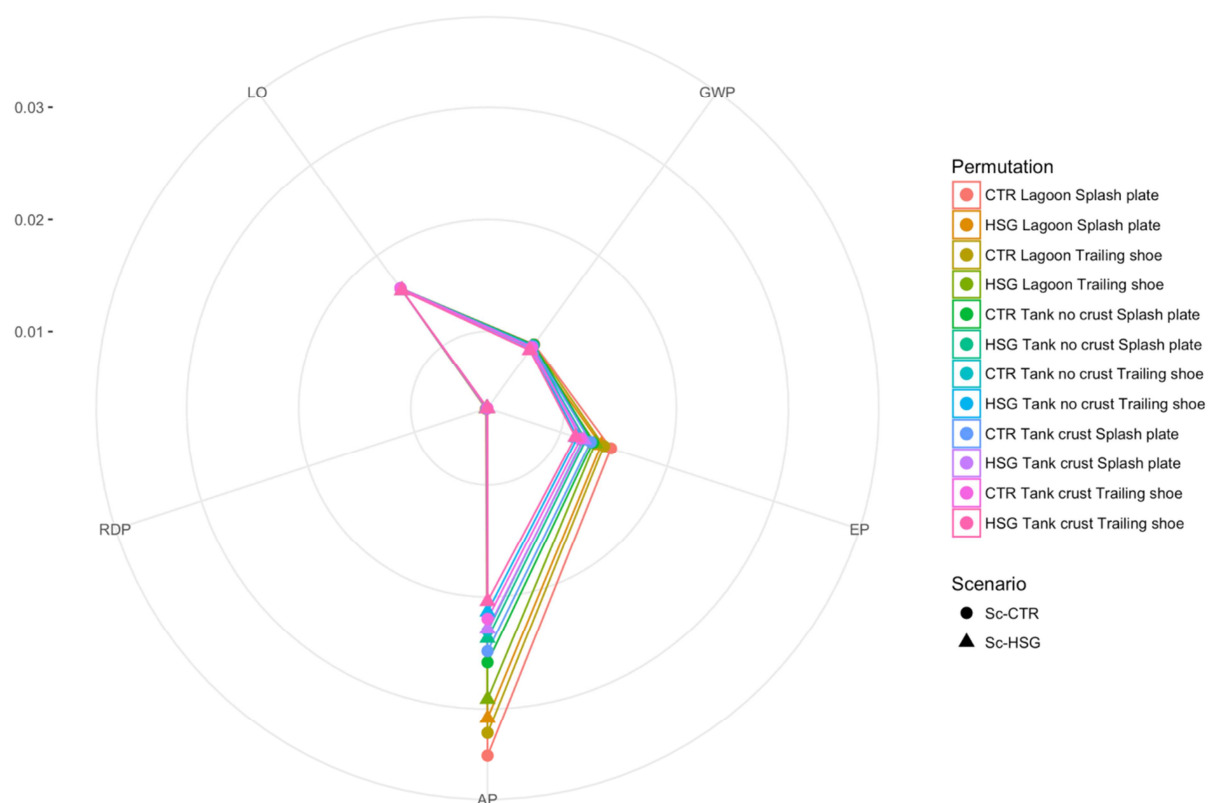
### 3.3. Hotspots

Energy and land required for dairy farming are limited by the availability of diminishing non-renewable resources and global land area respectively (Steinfeld et al., 2006). Pasture-based systems reduce reliance on imported land that is needed for the cultivation of concentrate feeds, and may also recycle energy resources on the farm (Soteriades et al., 2016; Styles et al., 2018). However, there remains large scope to improve on-farm land use and energy efficiencies. While for both Sc-CTR and Sc-HSG on-farm LO was about two thirds of total

LO (Table 2), the milk yields per ha on-farm land of these scenarios (8335 and 8901 kg raw milk per on-farm ha per year for Sc-CTR and Sc-HSG respectively- derived from data in sections 2 and S1) were notably lower than for similar systems, such as the New Zealand systems modelled in Basset-Mens et al. (2009). Similarly, a breakdown of RDP into main sources (Fig. 3 and S1) reveals that 75% of energy use occurred off-farm, for fertilizer manufacture and transport (50%) and concentrate feed cultivation, processing and transport (25%). On-farm diesel and electricity use represented 10% and 15% of life cycle energy use, respectively, and the primary energy inputs associated with electricity use also arise upstream of the farm. As pasture-based systems increasingly intensify (Gonzalez-Mejia et al., 2018), particular focus must be placed on efficiently using energy and land.

Normalization of environmental burdens per kg ECM against annual per capita loadings of an average European citizen indicate that milk production in grazing-based systems contributes particularly strongly towards AP, and not so strongly towards RDP, with similar relative contributions towards EP, GWP and LO. Through a reduction in N excretion and subsequent  $\text{NH}_3$  emissions, HSGs appear to mitigate a significant environmental hotspot of milk production. Tank storage and trailing shoe application of manures also have a notable effect on the AP hotspot (Fig. 5).





**Fig. 5.** Life Cycle Analysis impacts per kg energy-corrected milk, normalized against European per capita burdens. Sc-CTR: scenario with perennial ryegrass. Sc-HSG: scenario with high-sugar grass. GWP: global warming potential. EP: eutrophication potential. AP: acidification potential. RDP: resource depletion potential. LO: land occupation.

### 3.4. Sensitivity analyses

This subsection reports the results of the sensitivity analyses on the key emission factors, housing period and allocation method.

#### 3.4.1. Key emission factors

Previous studies have found that dairy systems with a more grass-based diet are more susceptible to uncertainty in emissions factors, which may be problematic when such systems are compared with more concentrate-based, housed systems (Flysjö et al., 2012; Gibbons et al., 2006). Sensitivity analyses on  $N_2O$ -N emission factors applied to N excreted during grazing; and on the  $N_2O$ -N factor applied to ammonium-nitrate fertilizer spread on grassland,

showed that GWP estimates per kg ECM were only 1.4–2.2% lower than the estimates reported earlier, thus they did not affect the robustness of the baseline results.

### 3.4.2. Housing period

Increasing the housing period from 120 days to 150, 180 and 210 did not affect the percent reductions in environmental impacts per kg ECM when shifting from one scenario permutation to another, as reported in Fig. 4 for the baseline results. The largest absolute difference between baseline (Fig. 4) and remodelled percent reductions was 1%, thus confirming the robustness of the baseline findings. Comparing burdens per kg ECM between baseline (Table 2) and remodelled scenarios (Tables S8, S9 and S10), it is noted that increasing the housing period had almost no effect on GWP and RDP (0–0.88% increase and 0–0.40% decrease in GWP and RDP, respectively, from baseline to remodelled scenarios), but slightly increased EP (0.19–1.57%) and AP (0.58–3.01%), owing to an increased amount of slurry stored.

### 3.4.3. Allocation method

Using the economic allocation method, about 74% of farm level burdens were attributed to milk production. This proportion was lower than the milk allocation factor derived from the energy allocation method and used earlier (about 85%). It was also lower than in other studies where milk production accounted for about 85–94.2% of total economic value (Basset-Mens et al., 2009; Guerci et al., 2013; Thomassen et al., 2008). One reason for this difference is that surplus heifers sold as in-calf heifers were also accounted for, in addition to cull cows and surplus calves. Another reason is that economic allocation is highly dependent on fluctuating prices. Indeed, changing the milk price data source from Redman (2017) to AHDB Dairy (2017), and removing heifer sales from the calculations, increased the milk

economic allocation factor from 74% to 80%, which is closer to the 85% value reported by Basset-Mens et al. (2009).

Although economic allocation decreased total impacts per kg ECM by 12–14% (Table S11), there was little differential effect between Sc-CTR and Sc-HSG, so the pattern of results was the same as earlier.

### 3.5. Comparisons with previous research and new insights

The results of this study agree with both an earlier review (Keim and Anrique, 2011) and meta-analysis (Foskolos and Moorby, 2017) that cattle fed on HSG excrete less urinary N, with the Sc-HSG scenarios resulting in a 16% reduction in urinary N excretion ( $\text{kg kg ECM}^{-1} \text{ day}^{-1}$  lactating per cow) relative to Sc-CTR. Moreover, two common performance indicators related to urine N (Foskolos and Moorby, 2017; Keim and Anrique, 2011; Moorby et al., 2006) from lactating cows were examined: the ratio milk N:urine N was lower for Sc-CTR cows (0.75) than for Sc-HSG cows (0.99), whilst the ratio urine N:dietary N was higher for Sc-CTR cows (0.35) than for Sc-HSG cows (0.29). These trends broadly agree with other HSG studies highlighting the potential benefits of HSG for reducing N emissions through reduced urine N (Miller et al., 2001; Moorby et al., 2006; Staerfl et al., 2012). The current study shows how this translates into significant reductions in EP and AP impacts in Sc-HSG relative to Sc-CTR (Table 2; Fig. 3–4 and S1). However, the benefit of reduced N excretion in Sc-HSG was moderated by the higher fertilizer application needed to compensate for fewer nutrients being returned to grass in manure (Defra, 2010; Table 1).

### 3.6. Practical implications and economic analysis

Switching to HSG is likely to be economically attractive owing to the higher productivity and feed conversion efficiency of HSG-based systems. When shifting from Sc-CTR to Sc-HSG,

the modelled farm could be earning an extra 15326 GBP or 115 GBP per cow from milk sales (Table 3; 1 GBP = 1.15 EUR = 1.42 USD on 19 April 2018), owing to an approximately 7% higher raw milk production (Table S5), and this difference would increase if the higher milk butterfat and protein yields for Sc-HSG (Table S5) had been accounted for. These findings are particularly important given the expansion of pasture-based systems as a cost-efficient form of milk production (Gonzalez-Mejia et al., 2018), but associated with higher enteric CH<sub>4</sub> emissions and N excretion per kg of milk compared with concentrate-based systems (Capper et al., 2009). High-sugar grasses can help to mitigate the environmental hotspots of such systems whilst improving productivity, maintaining the cost advantages and reducing the risk of indirect land use change associated with increases in maize (Vellinga and Hoving, 2011) and concentrate (Styles et al., 2018) feeding (Table 2).

The results also highlight the importance of investment in more advanced manure storage and spreading systems, supporting recent recommendations (Elliott et al., 2013) and justifying the focus of numerous training initiatives (AHDB Dairy, 2015, 2010a, 2010b) and financial aid (Defra, 2013a). Although improved manure management could lead to greater environmental savings than HSGs, the investment and physical disruption required to upgrade manure handling infrastructure and equipment (Misselbrook et al., 2005), and the more tangible link between HSG and increased productivity, is likely to make the establishment of HSG pastures a more attractive short-term measure for farmers. Indicatively, even though the costs of manure storage and spreading resulting from a 5.5% reduction in manure volume (data not reported) by shifting from Sc-CTR to Sc-HSG could save £4990 (£0.007 kg ECM<sup>-1</sup>) and £49896–£55440 (£0.070 kg ECM<sup>-1</sup>–£0.078 kg ECM<sup>-1</sup>) under lagoon and tank manure storage types, respectively, and it could also save another £252 (£0.00035 kg ECM<sup>-1</sup>) from manure spreading, the high costs of manure management are evident for both scenarios, even under the far less costly lagoon type of manure storage (Table 3). It has

452 been shown that technology adoption by dairy farmers is highly dependent on their peers'  
453 choice to adopt such technologies (Läpple and Kelley, 2015), suggesting that uptake of HSGs  
454 could be enhanced by targeting incentives to selected farmers who are well-connected in the  
455 farming community. Meanwhile, improved manure management could be driven by  
456 regulation and access to capital (Defra, 2013b).

457

458

459 **Table 3.** Profit gains from milk and cost reductions (total and per kg energy-corrected milk; ECM) in manure management when shifting from Sc-CTR<sup>a</sup> to Sc-HSG<sup>b</sup>.

	Milk production	Manure storage		Manure spreading
	income	Costs		costs
		Lagoon	Tank	
<b>Price (GBP) per unit</b>	£0.258 L <sup>-1c</sup>	£45 t <sup>-1d</sup>	£450–500 t <sup>-1d</sup>	£50 h <sup>-1e</sup>
<b>Sc-CTR<sup>a</sup></b>	£225791	£95159	£951588–£1057320	£4806
		(£0.098 kg ECM <sup>-1</sup> )	(£0.981 kg ECM <sup>-1</sup> –£1.088 kg ECM <sup>-1</sup> )	(£0.00495 kg ECM <sup>-1</sup> )
<b>Sc-HSG<sup>b</sup></b>	£241117	£90169	£901962–£1001880	£4554
		(£0.091 kg ECM <sup>-1</sup> )	(£0.911 kg ECM <sup>-1</sup> –£1.012 kg ECM <sup>-1</sup> )	(£0.00460 kg ECM <sup>-1</sup> )
<b>Difference</b>	-£15326	£4990	£49896–£55440	£252
<b>(Sc-CTR <i>minus</i> Sc-HSG)</b>		(£0.007 kg ECM <sup>-1</sup> )	(£0.070 kg ECM <sup>-1</sup> –£0.078 kg ECM <sup>-1</sup> )	(£0.00035 kg ECM <sup>-1</sup> )

460 <sup>a</sup> Scenario with perennial ryegrass (CTR- control). <sup>b</sup> Scenario with high-sugar grass (HSG). <sup>c</sup> Price for a *standard litre* of 4.1% butterfat and 3.3% protein (Redman, 2017, p.44), p.44. <sup>d</sup> Redman  
461 (2017, p.235). <sup>e</sup> NAAC (2017) data for tanker. Number of hours required for manure spreading estimated from volume of manure stored (data not reported) and manure application rates (t h<sup>-1</sup>).  
462 Manure application rates estimated as: slurry spreading costs per hour/slurry spreading costs per tonne = £40 h<sup>-1</sup>/£1.80 t<sup>-1</sup> = 22 t h<sup>-1</sup> (FAS, 2013, p.4). 1 GBP = 1.15 EUR = 1.42 USD on 19 April  
463 2018.

464

#### 4. Conclusion

Leakage of N compounds from agriculture is a major driver of global environmental problems, affecting human health, water, soil and air quality, biodiversity and climate (Sutton et al., 2011). Nitrogen excretion from grazing animals is a major source of N leakage (Bava et al., 2014) that may be mitigated through use of HSGs. The findings of this study suggest that re-seeding conventional ryegrass pastures with HSG ryegrass varieties improves productivity and leads to reductions in the environmental footprint of milk production, especially for AP and EP impacts. This supports the establishment of HSG pastures as an appropriate measure to encourage 'sustainable intensification' of dairy production, that is, increasing production in the least environmentally harmful manner (Foresight, 2011).

This study applied LCA and economic analyses to quantify the environmental and economic gains from switching the pasture source from conventional ryegrass to high-sugar grass on a simulated typical UK pasture-based dairy farm. The environmental and economic analyses were extended by generating 12 scenario permutations representing different manure spreading and storage methods.

It was found that the greatest environmental benefits are achieved by switching from conventional perennial ryegrass, lagoon and splash plate to HSG with trailing shoe and tank crust (with cover), leading to a reduction in EP and AP of up to 22 and 40% respectively. However, even a simple switch from conventional ryegrass to HSG under identical manure management led to notable reductions in the environmental footprint of milk, expressed per kg energy-corrected milk (e.g. EP and AP potentials  $\text{kg ECM}^{-1}$  could be reduced by 4–6% and 7–11% respectively). The use of HSG also increased milk production income and reduced manure management costs, owing to higher productivity and lower N excretion rates of Sc-HSG, yet manure management costs remained high.

This study shows that an easily achievable change in choice of grazing sward may deliver substantial environmental gains, especially when combined with improved farm technology. However, the high costs for improving manure management could drive expansion of HSG pastures as a more attractive short-term measure for farmers while investment in improved manure storage and spreading would require incentives, regulation or access to capital.

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ACCEPTED MANUSCRIPT

**Fig. 1.** Summary of methods illustrating sources of data and models used. <sup>1</sup> Grazing period. <sup>2</sup> Indoor period.

**Fig. 1.** Main inputs, processes and products accounted for within the system boundaries to calculate impact per kg of energy-corrected milk.

**Fig. 3.** Life Cycle Analysis impacts per source for trailing shoe. CTR: scenario with perennial ryegrass. HSG: scenario with high-sugar grass. GWP: global warming potential. EP: eutrophication potential. AP: acidification potential. RDP: resource depletion potential.

**Fig. 4.** Summary of the percent reductions in environmental impacts per kg energy-corrected milk when shifting from perennial ryegrass (CTR) to high-sugar grass (HSG) and/or when improving manure storage facility (from lagoon to tank without crust cover to tank with crust cover) and manure spreading method (from trailing shoe to splash plate). Sc-CTR: scenario with perennial ryegrass (CTR- control). Sc-HSG: scenario with HSG. GWP: global warming potential. EP: Eutrophication potential. AP: acidification potential. RDP: resource depletion potential.

**Fig. 5.** Life Cycle Analysis impacts per kg energy-corrected milk, normalized against European per capita burdens. Sc-CTR: scenario with perennial ryegrass. Sc-HSG: scenario with high-sugar grass. GWP: global warming potential. EP: eutrophication potential. AP: acidification potential. RDP: resource depletion potential. LO: land occupation.

**Fig. S1.** LCA impacts per source for splash plate.

- Environmental footprints of a ‘typical’ pasture-based UK dairy farm were calculated
- Two pasture scenarios modelled: conventional perennial ryegrass v. high-sugar grass
- Six manure management scenarios were also modelled
- Both high-sugar grasses and improved manure management notably reduced footprints
- High-sugar grasses are a more economical short-term measure for reducing footprints